Towards per datum error characterization for radio occultation retrieval products

Chi O. Ao, Byron A. Iijima, Anthony J. Mannucci, Panagioits Vergados, Olga P. Verkhoglyadova, and Kuo-Nung Wang

Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA

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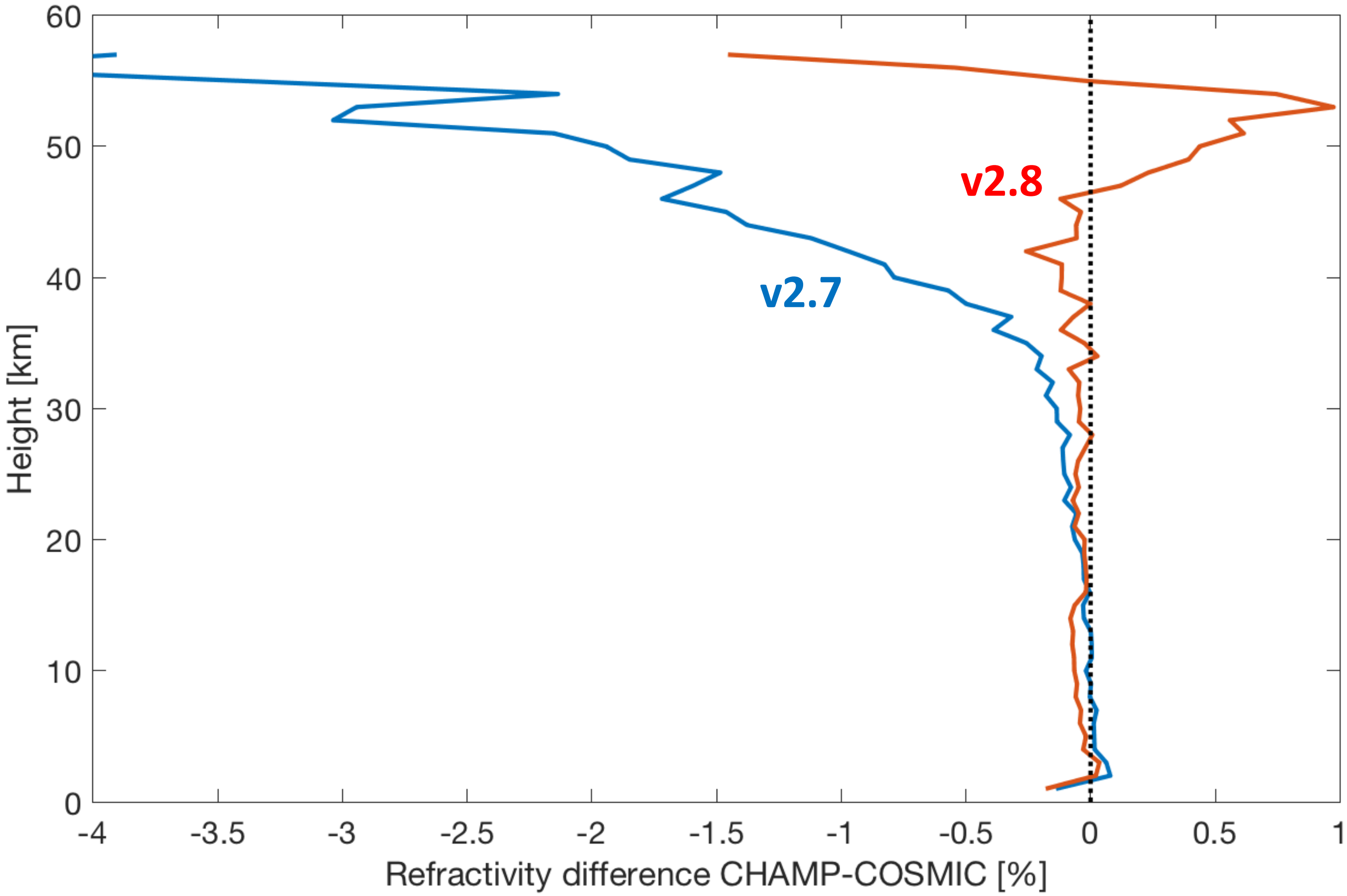
Outline

- RO processing updates at JPL
- Approach in uncertainty estimates
- Results from CHAMP and COSMIC
- Summary

RO processing at JPL

- **Goal**: a consistently processed RO data record from NASA/JPL receivers that includes CHAMP, SAC-C, GRACE, COSMIC, TSX, TDX, and KOMPSAT-5 from Level 0 to Level 3.
- **Recent changes**:
  - Cubic (previously quadratic) smoothing of phase to reduce biases above 20 km altitude where smoothing intervals are larger (v2.7).
  - New Abel high-altitude initialization that aims to reduce bias from noisy measurements (which may impact consistency from different missions) and reduce retrieval failures (v2.8 – in progress).

CHAMP/COSMIC collocations < 300 km, 2 hr



Motivation: Establishing GNSS RO as reference observations

- Following the GRUAN (GCOS Reference Upper Air Network) paradigm:

✓ *Is traceable to an SI unit or an accepted standard*

✓ *Provides a comprehensive uncertainty analysis*

✓ *Is documented in accessible literature*

✓ *Is validated (e.g. by intercomparison or redundant observations)*

✓ *Includes complete meta data description*

✓ ***Important to distinguish contributions from systematic error and random error***

Some existing works

Kursinski et al. 1997

- Comprehensive theoretical analysis with multiple error sources.

Kuo et al. 2005

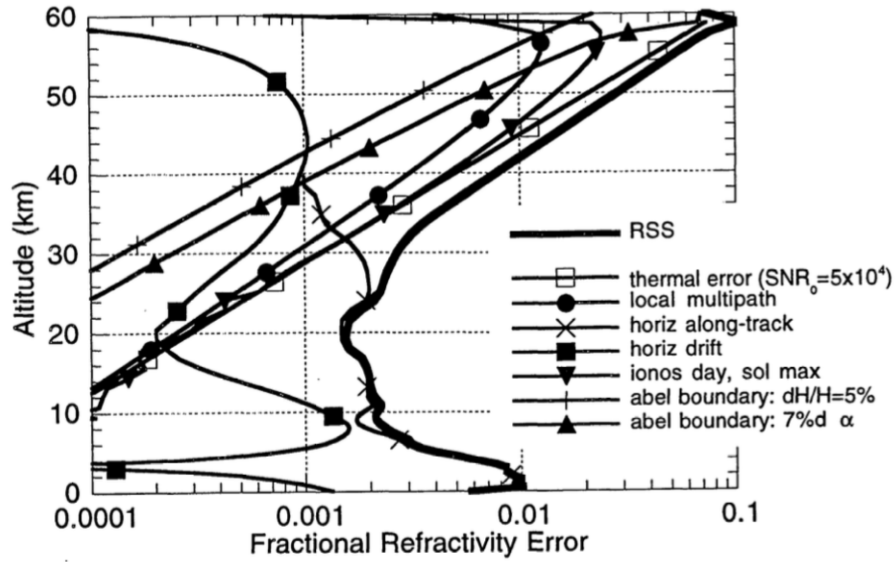
- Derived error estimates based on actual retrieval comparison with NWP forecasts.

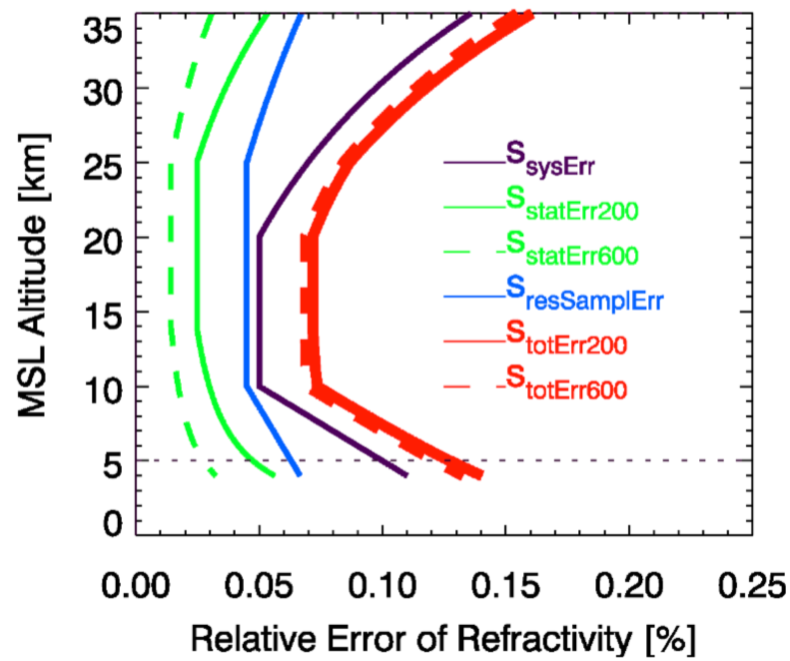
Scherlin-Pirscher et al. 2011

- Explicit separation of systematic and random errors, plus sampling error for climatological averages.

Schwarz et al. 2017

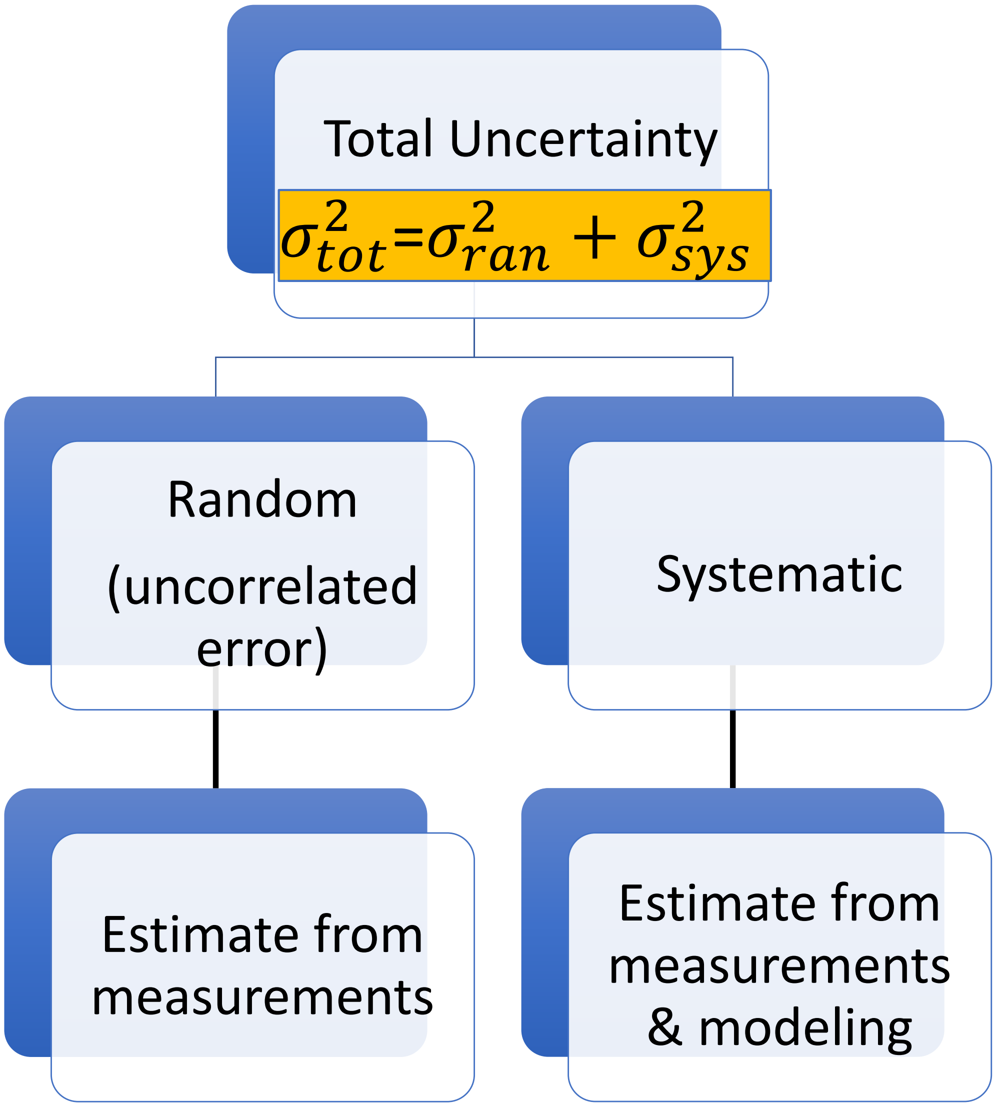
- Detailed error estimate and propagation.
- Similar objectives as ours.





Independent uncertainty estimates specific to a retrieval system are desirable.

Uncertainty estimation (separate random & systematic)



Contributions that will average out in climatology (e.g., horizontal variability, local multipath)

Contributions that will not average out (e.g., iono residual)

Random errors: Bending angle

Estimate phase noise from the L1 and L2 excess phase data:

1. Detrend phase and compute standard deviation over 1 sec to get the 1-sec phase noise.
2. Scale to actual smoothing interval *T*-sec if needed.
3. Derive bending angle uncertainty using the following expressions [Hajj et al. 2002]:

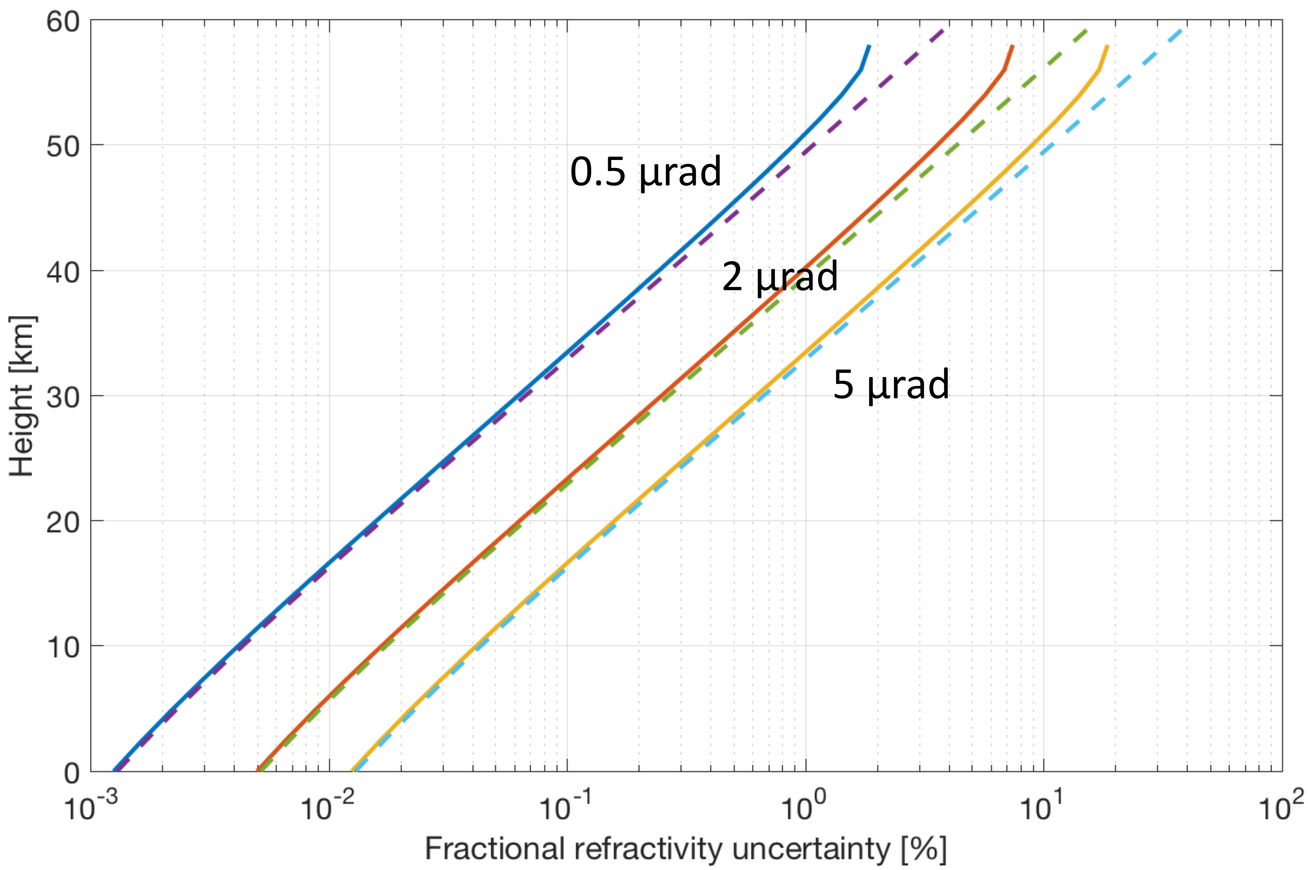
$$\sigma_i(M) \approx \frac{c}{f_i V}\left(\frac{\nu \sigma_\phi}{\Delta t\ M^{3/2}}\right)$$

Δt = sample time (e.g., 20 msec)
M = number of data points in the smoothing interval (e.g., 50)
V = tangent point velocity (e.g. 2 km/s)

$$\sigma_n^2 = \sigma_1^2(M_1) + (1.54)^2 \underbrace{\left[\sigma_1^2(M_2) + \sigma_2^2(M_2)\right]}_{\text{Coarse smoothing } (M_2 > M_1)}$$

Random errors: Refractivity

$$\sigma_j^{(N)} = \left[\sum_{i=j+1}^{M} F_{ji}^2 \sigma_i^2 \right]^{1/2} \quad \text{where} \quad F_{ji} = \frac{10^6}{\pi} \frac{\delta a_i}{\sqrt{a_i^2 - a_j^2}}$$



Solid lines: BA contribution from impact height < 60 km

Dashed lines: impact height < 80 km

Sources of systematic BA errors

Not an exhaustive list!

1. **Residual ionosphere**
2. Horizontal inhomogeneity
3. Local multipath
4. POD (pos, vel, clock)

For lower troposphere:

5. Tracking error? [Zus et al. 2014]
6. Retrieval nonlinearity? [Sokolovsiy et al. 2010]

Systematic errors: Refractivity

- From systematic error of BA:

$$\langle \Delta N_j \rangle = \sum_{i=j+1}^{M} F_{ji} \langle \Delta \alpha_i \rangle$$

- Abel Upper Boundary (UB) condition introduces uncertainty in refractivity. For exponential extrapolation above a_u, we estimate the refractivity uncertainty at a_j below a_u due to scaleheight H uncertainty as

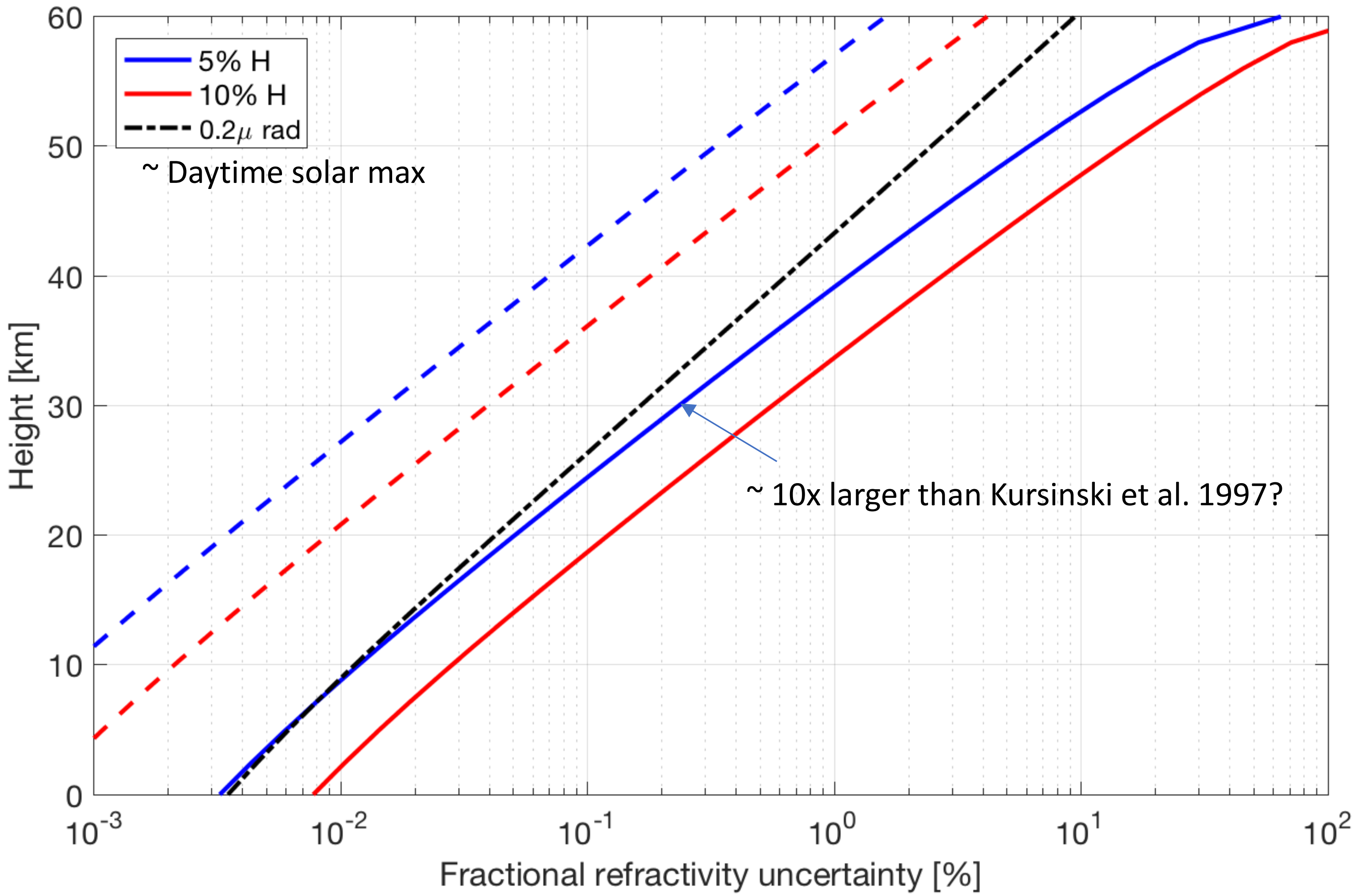
$$\langle \Delta N_j \rangle^{(U)} = U_j(H \pm \Delta H) - U_j(H)$$

ΔH will be determined based on residuals to each fit

where U is given by [Gleisner and Healy, 2013]

$$U(a; H) \approx 10^6 \alpha_u e^{-(a-a_u)/H} \sqrt{\frac{H}{2\pi a}} \operatorname{erfc}\left(\sqrt{\frac{a_u - a}{H}}\right)$$

Iono & UB errors

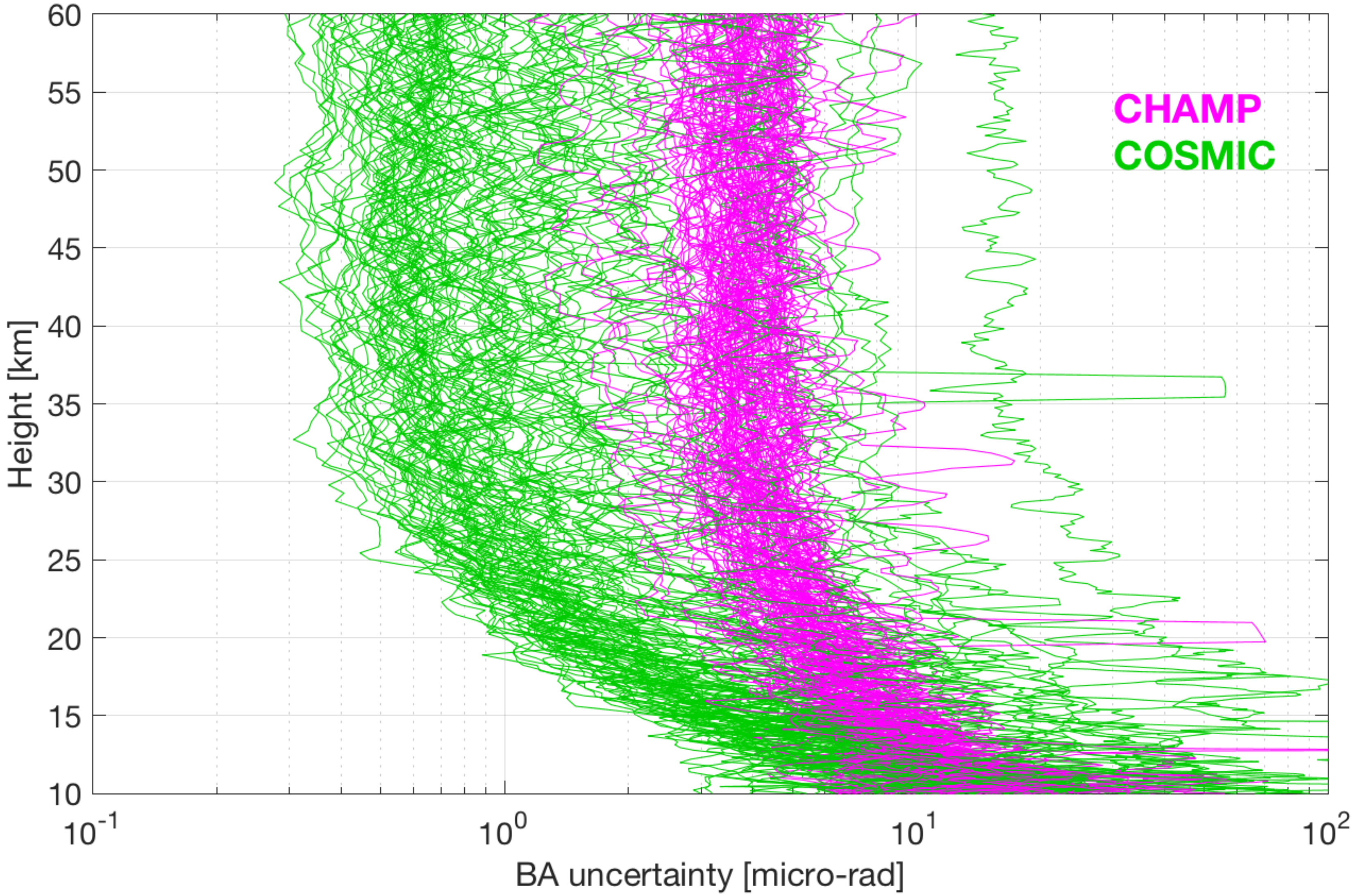


Solid lines:
h_u= 60 km

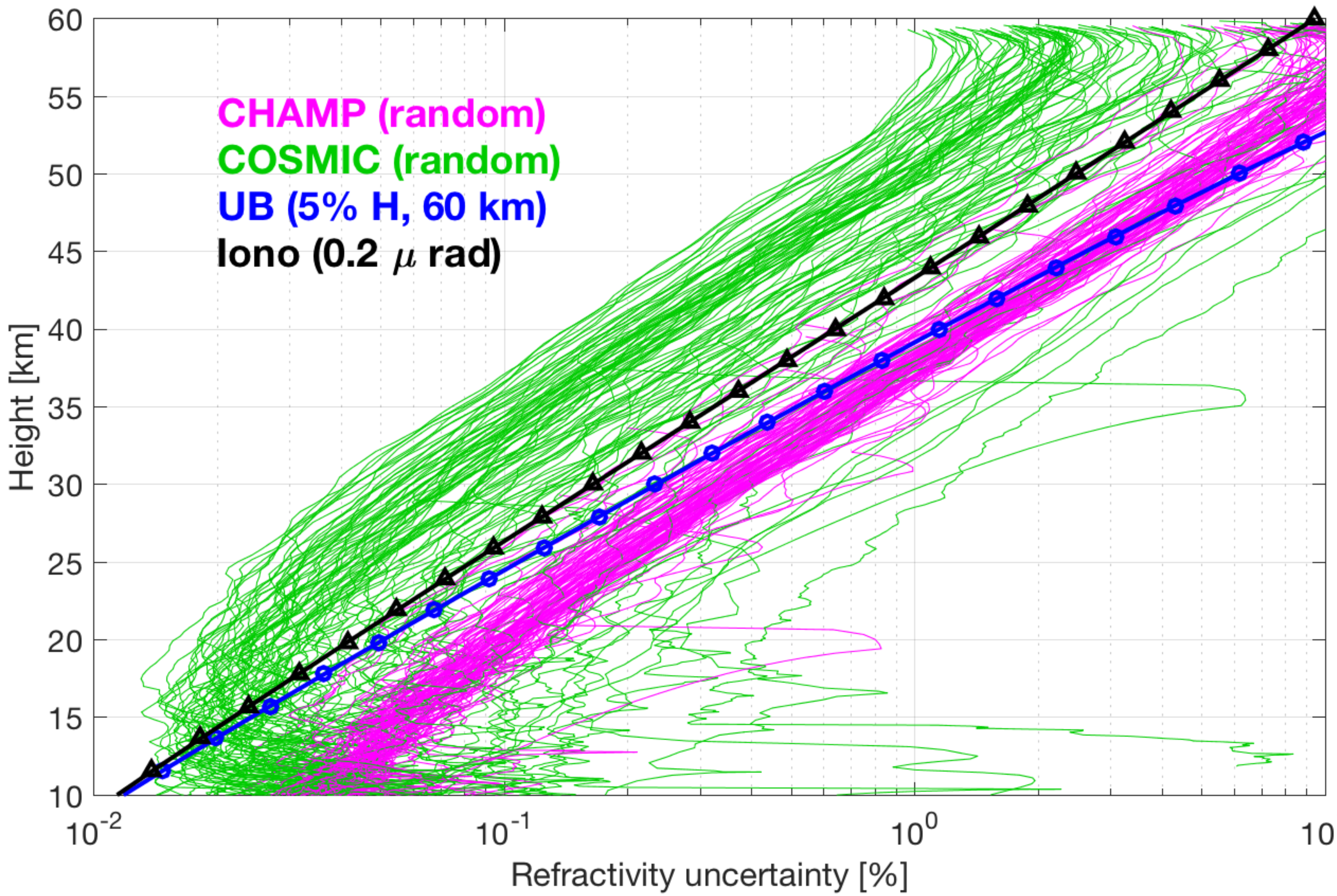
Dashed lines:
h_u= 80 km

Examples from CHAMP & COSMIC

Estimated random BA uncertainty



Examples from CHAMP & COSMIC

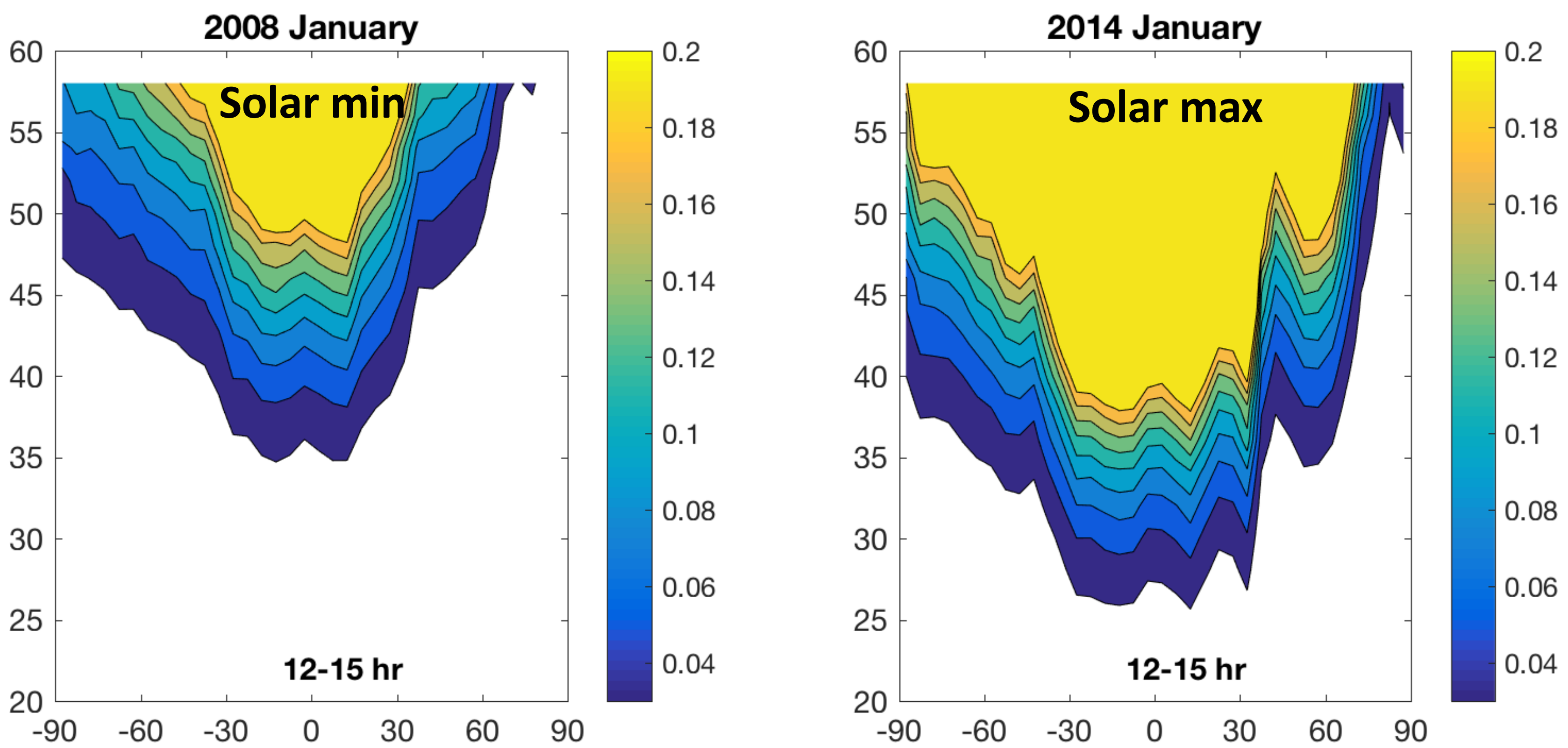


Better estimate of iono error

$$\alpha_c(a) = \alpha_{L1}(a) + \frac{f_2^2}{f_1^2 - f_2^2}(\alpha_{L1}(a) - \alpha_{L2}(a))$$

$$\boxed{+\kappa(a)(\alpha_{L1}(a) - \alpha_{L2}(a))^2,}$$

Healy and Culverwell, 2015



Kappa = 14

Summary

- Progress towards per datum uncertainty characterization of RO retrieval products at JPL.
- A few dominant error sources have been considered so far.
- Uncertainty estimates need to be verified (through comparisons with other data, RO pairs, etc.) and refined.
- Per datum uncertainty gives an effective approach in quality control.